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Doubling Main Injector Beam Intensity using RF Barriers

K.Y. Ng

Fermi national Accelerator Laboratory, P.O. Box 500, Batavia, IL 60540

Abstract. Using rf barriers, 12 booster batches can be injected into the Fermilab Main Injector continuously, thus doubling the usual beam intensity. After that, adiabatic capture of the beam into 53 MHz buckets can be accomplished in about 10 ms. The beam loading voltages in the rf cavities are small and they can be eliminated by a combination of counterphasing and mechanical shorts.

THE INJECTION METHOD

Instead of slip-stacking [1], a method to double beam intensity in the Main Injector by rf barriers without adiabatic bunch compression was proposed by Griffin [2]. A booster batch of protons of length T_b and full fractional momentum spread Δ, denoted by 1 in Fig. 1(a) is injected into the Main Injector at a *negative* momentum offset, so that the highest fractional momentum offset is δ_{i1} and the lowest fractional momentum offset is $\delta_{i2} = \delta_{i1} - \Delta$. The longitudinal position of the injection is so chosen that the right side of the batch just touches the left side of a square barrier B of width T_1 and magnitude V, which is moving to the left at the speed of $\dot{T}_2 = T_b/(2T_c)$ where T_c is the booster-cycle time. The momentum offset of the batch injection is so chosen that protons of highest energy on the left side of the batch will drift to the right at the speed of $\frac{1}{2}T_b$ per booster cycle or $-\dot{T}_2$. Thus, after one booster cycle, another batch marked 2 in Fig. 1(b) can be injected again with its right edge touching the left side of the barrier. In other words, at every booster cycle, a new booster batch can be injected with the injection point moved half a booster-batch length to the right. The linear beam density can therefore be doubled.

The only parameter here is the strength of the barrier,

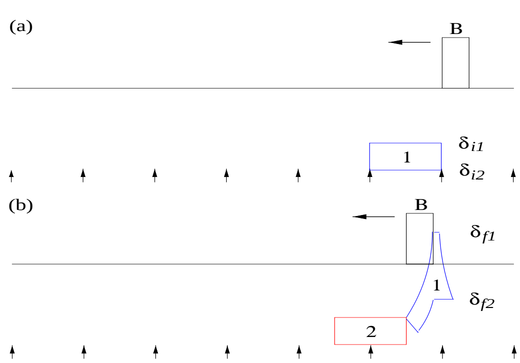


FIGURE 1. (a) Booster batch 1 is injected at negative momentum offset with the right edge just touching a left-moving barrier B. The vertical arrows are spaced one booster-batch length T_b apart. (b) After a booster cycle, the barrier moves by half a booster-batch length while all particles in batch 1 drift past the left edge of the barrier. Exiting the barrier, the batch has maximum and minimum momenta, δ_{f1} and δ_{f2}, equal and opposite. Another booster batch 2 is now injected.

which is so chosen that after the booster batch emerges from the barrier, the highest and lowest energies of the batch become symmetric about the nominal energy of the accelerator ring. This is necessary because we need to place another stationary barrier on the right side of the moving barrier in order to limit the longitudinal motion of the protons after passing through the moving barrier so as to guarantee empty spaces along the Main Injector for future batch transfer from the Booster. We use a rectangular barrier here just for simplicity, although the results depend only on the integrated strength of the barrier.

To derive the strength of the barrier, let us go to a more general scenario of having the barrier moving to the left at the rate of $\dot{T}_2 = xT_b/T_c$ ($x = \frac{1}{2}$ in above). Suppose the first proton with momentum spread δ_{i1} exits the barrier in the N_1 turns. Its phase drift in time towards the right is

$$\int_0^{N_1} \eta T_0(\delta_{i1} + n\Delta\delta)dn\,, \tag{1}$$

where η is the slip factor, T_0 is the revolution period, $\Delta\delta = eV/(\beta^2 E)$, e is the proton charge, E is the on-momentum proton energy with βc its longitudinal velocity and c the velocity of light. At this moment, the barrier has moved towards the left by the phase $N_1\dot{T}_2T_0$. Because the width of the barrier is T_1, we must have

$$T_1 - N_1\dot{T}_2T_0 = \int_0^{N_1} \eta T_0(\delta_{i1} + n\Delta\delta)dn\,, \tag{2}$$

from which N_1 can be solved. The exit momentum spread of this particle is therefore

$$\delta_{f1} = \frac{\dot{T}_2}{|\eta|} - \sqrt{\left(\delta_{i1} - \frac{\dot{T}_2}{|\eta|}\right)^2 - \frac{2T_1\Delta\delta}{|\eta|T_0}}\,. \tag{3}$$

The final fractional momentum offset δ_{f2} of the protons with the lowest initial momentum spread δ_{i2} can be obtained similarly. Equating the two, we arrive at the strength of the barrier

$$VT_1 = \frac{T_0T_b^2\beta^2E}{2|\eta|T_c^2}\left[1 - \left(\frac{\Delta|\eta|}{2\dot{T}_2}\right)^2\right]\left[\left(1 + \frac{x\Delta|\eta|}{2\dot{T}_2}\right)^2 - x^2\right], \tag{4}$$

where use has been made of the fact that the protons with initial momentum spread δ_{i1} must drift to the right at a rate of $(1-x)T_b/T_c$ so that a next batch can be injected or $\delta_{i1} = -(1-x)\dot{T}_2/(x|\eta|)$.

Obviously, a larger initial fractional momentum spread Δ of the beam will lead to a larger final fractional momentum spread. However, when the initial fractional momentum spread is large enough, protons with the highest momentum will acquire so much energy from the moving barrier that their drifting speeds to the left exceed the speed of the moving barrier. These particles will not be able to emerge from the moving barrier and this injection method fails. This happens when $\dot{T}_2 < |\eta|\delta_{f1}$, resulting in the critical strength of the moving barrier

$$(VT_1)_c = \frac{T_0 T_b^2 \beta^2 E}{2e|\eta|T_c^2} , \tag{5}$$

which is independent of x, and the maximum allowable initial full fractional momentum spread of the beam is

$$\Delta_c = \left(\sqrt{x^2+\frac{1}{4}}-\frac{1}{2}\right)\frac{2T_b}{|\eta|T_c} . \tag{6}$$

For a given full fractional momentum spread Δ of the beam, the speed of the moving barrier must be faster than xT_b/T_c where

$$x = \sqrt{\frac{|\eta|T_c\Delta}{2T_b}\left(\frac{|\eta|T_c\Delta}{2T_b}+1\right)} . \tag{7}$$

EMITTANCE INCREASE

The position of injection along the accelerator ring slips to the left by xT_b for each injection or for each booster cycle. implying that a whole batch of length T_b of beam can be injected in the length xT_b. Therefore the ratio of final to initial emittances is

$$r_e = \frac{\delta_{f1}\times 1}{\frac{\Delta}{2}\times\frac{1}{x}} = 1+\frac{|\eta|T_c\Delta}{2T_b} , \tag{8}$$

which is independent of x. Here, we assume circumference of the accelerator ring is infinitely long so that injection can be continued forever. On the other hand, the final linear density does increase by the factor $r_d = 1/x$. For this reason, we should choose the lowest barrier moving speed allowable by the initial momentum spread of the batch. In other words, given Δ, we should stick to the critical x given by Eq. (7) and the critical size $(VT_1)_c$ for the barrier given by Eq. (5).

APPLICATION TO MAIN INJECTOR

Simulations were performed for doubling the Main Injector intensity at the injection energy of $E = 8.938$ GeV at the critical condition for barrier movement of $\frac{1}{2}T_b$ per booster cycle ($x = \frac{1}{2}$) with the initial half critical half energy spread of $\Delta E_{\frac{1}{2}i} = 4.900$ MeV. Here, $T_b = 1.59$ μs, $T_0 = 7T_b$, $T_c = 0.667$ ms, $\eta = -0.00892$ and the critical barrier strength is $(VT_1)_c = 3.1421$ kV-μs. Particles with the highest energy are injected with the offset of $\Delta E_{i1} = -\dot{T}_2\beta^2E/|\eta| = -11.8285$ MeV while particles with the lowest energy are injected with offset $\Delta E_{i2} = \Delta E_{i1} - 2\Delta E_{\frac{1}{2}i} = -21.6276$ MeV. After exiting the moving barrier, their final energy offsets are $\Delta E_{f1} = -\Delta E_{i1} = 11.8285$ MeV and $\Delta E_{f2} = -\Delta E_{f1} = -11.8285$ MeV. Thus, the energy spread has been increased by the factor $\Delta E_{f1}/\Delta E_{\frac{1}{2}i} = 11.8285/4.8995 = 2.419$ and this is also the ratio of the final longitudinal emittance to the initial longitudinal emittance. Figure 2 shows the situation one booster cycle after the injection of the 12th batch. The consecutive bunches are represented by different colors for easy identification. The vertical dashed lines separate the ring into 7 booster lengths and the first batch was injected at the location between 5.5 and $6.5T_b$. The reflecting barrier is represented by the solid square at location $7T_b$, while the injection barrier is represented by the hollow square with the arrow pointing to its direction of motion. Theoretical reasoning and simulations show that about 10 ms will be required to capture the beam into the 53-MHz buckets.

Barriers are usually used to confine a beam within a designated region along the accelerator ring. The integrated sizes of the barriers need not be accurate as long as they are large enough to confine the particles of the highest and lowest energies. However, this is not true here. Although the injection process does not depend on the shape of the moving barrier, its integrated size has to be accurate in order to have the final positive and negative energy spreads be equal and opposite. Otherwise, after reflection by the stationary barrier, the positive energy spread will be modified, resulting possibly in an increase in the longitudinal emittance. Here, we would like to study the effect of such an error. The left plot of Fig. 3 shows the situation when VT_1 is 10% larger than its critical value, 2 booster cycle after the injection of the 12th bunch. Actually the final momentum spread becomes smaller. However, many particles cannot emerge from the strong barrier resulting in a loss of 10.6%. The situation of a reduction of VT_1 by 10% from its critical value is shown in the right plot. Now all particles will emerge from the moving barrier earlier and their energies

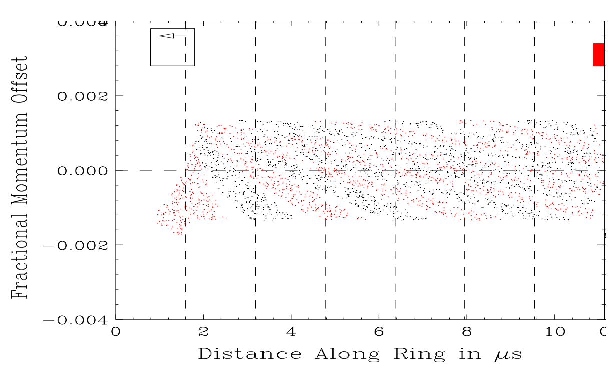
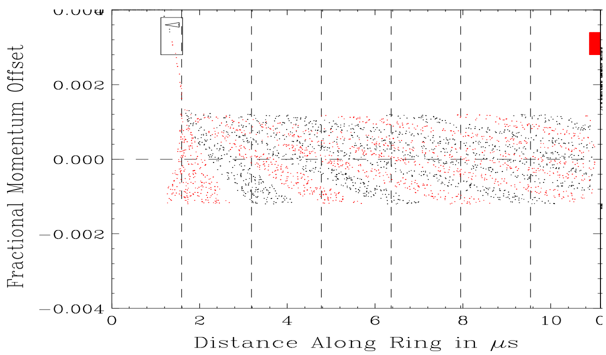


FIGURE 2. (color) Longitudinal phase space one booster cycle after the injection of the 12th batch between



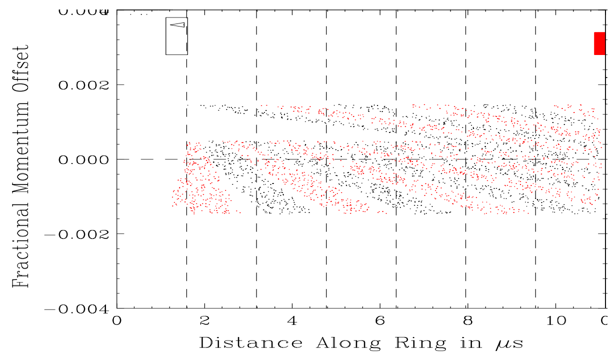


FIGURE 3. (color) Plots showing 2 booster cycle after injection of 12th bunch, with the strength of the moving barrier (left) increased by 10% and (right) decreased by 10%.

are therefore reduced, which results in an increase in momentum spread by 9.8% after reflection by the stationary barrier. A small amount particles have energies high enough that their left-drift velocities after reflection are larger than that of the moving barrier. Eventually, they may catch up with the moving barrier and get lost.

BEAM LOADING

Because of the high beam current, the problem of beam loading must be examined. At the passage across the $N_c = 18$ rf cavities, a very short bunch containing 6.0×10^{10} protons will induce a total instantaneous beam loading voltage $V_{b0} = qN_c\omega_r R_L/Q_L = 5.5$ kV, where $R_L = 500$ kΩ, $Q_L = 5000$, and $\omega_r/(2\pi) = 52.8$ MHz are, respectively, the loaded shunt impedance, loaded quality factor, and resonant frequency of each cavity. For a batch of 84 such bunches injected into the Main Injector, the beam loading voltage after the passage of the last bunch increases to 444 kV. Thus the difference in beam loading voltages experienced by the last and first bunches is 439 kV. Taking into account of the finite lengths of the bunches, this difference becomes 388 kV when steady state is reached. During normal operation, the total rf voltage at injection is 1.2 MV. If the designed synchronous phase $\phi_s = 0$ is synchronized to the middle bunch of the batch, the rf phase errors introduced become $\Delta\phi_s = \pm 9.18^\circ$ for the first and last bunches. Eventually, the longitudinal emittances of the bunches will be increased up to 18%, which is considered still tolerable.

During slip-stacking, although the bunch density is doubled, the beam loading voltage may not increase because the bunch spread out to almost fill the buckets at the very low rf voltage of ~ 64 kV, almost 7 times less than the difference in beam loading voltages seen by the first and last bunches. Such low rf voltage is required in order to allow two series of buckets to stay within the momentum aperture of the ring. The rf phase errors now become so large that the most beam particles will be driven out of the buckets. Feedforward and feedback have been planned to compensate for the beam loading.

In the present continuous multiple injection scheme using barriers, the booster bunches before injection will be made very long in the Booster so that the momentum spread can be reduced. These bunches start to debunch immediately after injected into the Main Injector. For a completely uniformly distributed beam, there is no 53 MHz rf component and therefore no beam loading at all. Here, although the distribution is not uniform (see, for example, Fig. 2), the 53-MHz rf component of the beam current at any moment of the injection is found to be less than 0.25% of twice the dc beam current, implying that the beam loading voltage will be reduced at least 400 times.

Actually no rf voltage is required in this injection scheme. The Main Injector is presently equipped with fast mechanical shorts, which can be inserted in 100 ms and removed in 50 ms [4]. To cope with beam loading and arrive at zero rf voltage, first, the rf drive of 16 cavities is turned off and shorts are inserted. Second, counterphasing is used for the two remaining cavities to arrive at zero rf voltage with the tiny beam loading voltage taken into consideration. Further fine adjustment can be implemented using a fast low-level feedback. Notice that counterphasing is not possible for slip-stacking because the two rf controls have been employed already to produce the two series of buckets at slightly different frequencies.

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